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**PRELIMINARY STUDY OF SATELLITE ATTITUDE
DETERMINATION FOR THE LANDSAT 7 SPACECRAFT**

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STRATEGIC AND SPACE SYSTEMS DEPARTMENT

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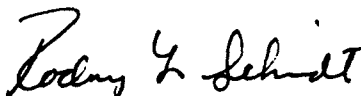
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FOREWORD

This report explores the use of multiple data sources to support satellite attitude determination for the LANDSAT 7 spacecraft. This study was initiated at the direction of the Defense Mapping Agency (DMA) as a means of understanding how attitude could be refined in order to exploit LANDSAT 7 stereo pairs for mapping and charting.

The work was performed in the Space and Surface Systems Division of the Strategic and Space Systems Department. This report has been reviewed by James L. Sloop, Head, Space and Surface Systems Division.

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ABSTRACT

This report presents the results of an error analysis for satellite attitude determination for the LANDSAT 7 spacecraft. The purpose of this study was (1) to evaluate the contribution of dual-antenna Global Positioning System (GPS) measurements to spacecraft attitude uncertainty and (2) to determine if spacecraft attitude could be determined to an accuracy that would allow direct mapping from LANDSAT 7 stereo pair imagery. Although preliminary, the results indicate that GPS measurements have the potential to improve spacecraft attitude if certain technical goals can be achieved associated with GPS instrumentation. The useability of stand-alone stereo pairs for direct mapping, satisfying Defense Mapping Agency (DMA) product standards, is questionable due to correlated stellar sensor errors.

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INTRODUCTION

The ability to estimate precise attitude for the LANDSAT 7 spacecraft will be a determining factor for exploiting single-pass stereo pair imagery for mapping without the need for large area photogrammetric triangulation. As initially designed, spacecraft attitude during the mission would be determined from a combination of stellar sensor and rate gyro data. However, these sources of orientation information are not sufficiently accurate to preclude the need for photogrammetric triangulation. Therefore, it was prudent to explore alternative means for possible enhancement of mission attitude determination. The data sources considered to augment the design were Global Positioning System (GPS) dual-antenna phase measurements and stereo pair mensuration.

As a first step in understanding what accuracy might be achievable, a preliminary, one-dimensional spacecraft attitude study was performed. This study examined four data types in a least squares covariance analysis of satellite attitude determination. The measurement types considered are listed in Table 1. The rate at which these observations would be acquired or processed and their nominal precision, in terms of how accurately orientation can be obtained from the measurements, is also provided. Nominal precision should be interpreted to mean subsystem specifications in the case of stellar attitude and rate gyro stability, a technology performance goal for GPS attitude determination, and an anticipated capability from stereo mensuration based on image pixel size and ground coverage provided by a typical stereo pair.

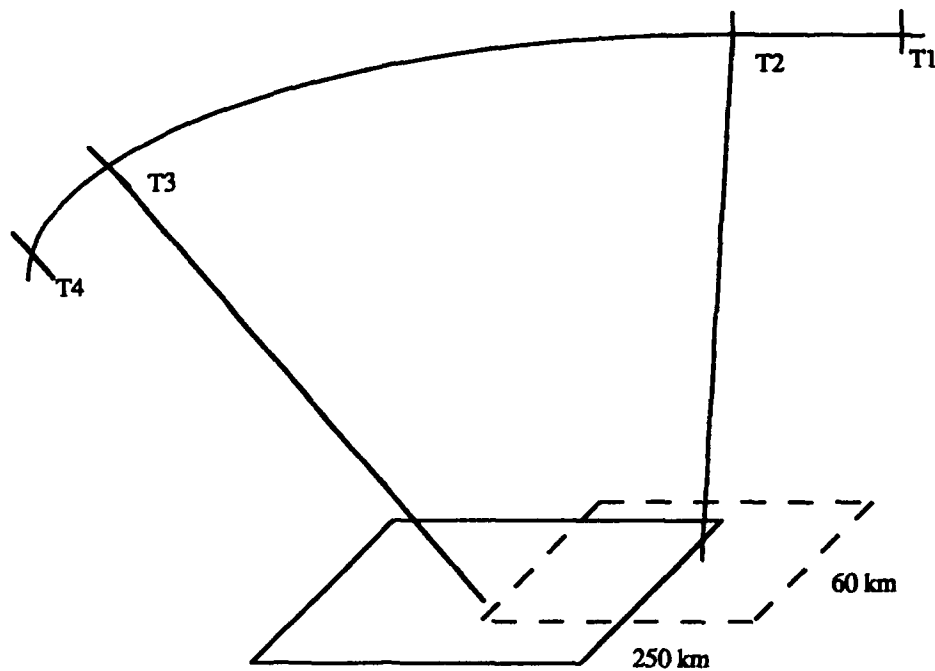
TABLE 1. LANDSAT 7 DATA TYPES USED IN COVARIANCE ANALYSIS

Data Type	Data Rate	Nominal Precision
Stellar Attitude (Celestial Sensor Assembly)	2 per image operation	4 arcsec random bias 2.7 arcsec random noise
Gyro Derived Attitude Change	1 per second ¹	0.01333 arcsec/sec
GPS Attitude (Phase Derived)	1 per second	36 arcsec ²
Stereo Pair Mensuration (Relative Orientation)	1 per image pair	5.8 arcsec

¹0.1 sec rate is available, 1 sec rate considered in analysis

²Based on goals of a Naval Research Laboratory (NRL) Satellite Program (1995)

Figure 1 provides a sense of the geometry of LANDSAT 7 stereo pair acquisition. The imagery and support data collection takes place during a 3-min interval. This image acquisition scenario was the basis for a covariance analysis, which assumed the data sources described in Table 1 were collected or derived from measurements at the specified rates. Stellar attitude was assumed to be measured at the endpoints of the time interval spanning T_1 to T_4 . The images were assumed to be instantaneously acquired at T_2 and T_3 separated in time by 120 sec. In addition to stellar attitude, orientation changes were assumed to be continuously provided by rate gyro data and it was assumed that GPS orientation was determined from dual-antenna phase measurements at a 1-sec rate. Image mensuration provided the relative orientation of the stereo pair.



$$T_2 - T_1 = T_4 - T_3 = 30 \text{ sec}$$

$$T_3 - T_2 = 120 \text{ sec}$$

FIGURE 1. GEOMETRY OF LANDSAT 7 IMAGERY
(OVERLAP UNDERREPRESENTED)

ATTITUDE DYNAMICS MODEL

Over the time interval from T_1 to T_4 , during the image operation, the attitude dynamics of the spacecraft (one-dimensional model) was assumed to be given by a polynomial of degree three:

$$\theta = at^3 + bt^2 + ct + d$$

where a , b , c , and d are model parameters to be estimated and t is the number of seconds from T_1 . Of particular importance are the uncertainties in spacecraft attitude at imaging times T_2 and T_3 .

Since stellar and GPS attitude provide absolute measures of orientation, these data will contribute to all attitude model unknowns. Rate gyro data and image mensuration will provide angular change and relative image orientation, respectively, and thus, contribute to a determination of only three of the four parameters of the attitude model.

MEASUREMENT MODELS AND STATISTICAL PROPERTIES

This section presents the measurement models that were incorporated into the spacecraft attitude analysis presented below. For each measurement type, the mathematical model is provided along with the measurement's statistical representation and the design matrix used in the development of the covariance analysis.

STELLAR ATTITUDE

Stellar attitude data were assumed to be measured at each end of a 180-sec imaging interval assuming an error structure consisting of a random bias and a random (white noise) component. At times T_1 and T_4 , the stellar sensor will provide estimates of spacecraft orientation given by

$$\theta^o_1 = \theta_1 + \varepsilon(T_1)$$

and

$$\theta^o_4 = \theta_4 + \varepsilon(T_4)$$

where $\varepsilon_1 = \varepsilon(T_1)$ and $\varepsilon_4 = \varepsilon(T_4)$ represent errors in stellar attitude having the characteristics (see Table 1):

$$\varepsilon_1 = \alpha + \eta_1$$

$$\varepsilon_4 = \alpha + \eta_4$$

where the random bias α has a nominal standard deviation of 4.0 arcsec and the random error η has a nominal standard deviation of 2.7 arcsec. Thus, the variance and covariance for the errors ε_1 and ε_2 are given by

$$E[\varepsilon_1 \varepsilon_1] = E[\varepsilon_4 \varepsilon_4] = \alpha^2 + E[\eta_1 \eta_1] = \alpha^2 + E[\eta_4 \eta_4]$$

$$E[\varepsilon_1 \varepsilon_4] = E[\varepsilon_4 \varepsilon_1] = \alpha^2$$

The covariance matrix for the pair of stellar updates is thus,

$$\Sigma_\varepsilon = \begin{bmatrix} \alpha^2 + E[\eta_1 \eta_1] & \alpha^2 \\ \alpha^2 & \alpha^2 + E[\eta_4 \eta_4] \end{bmatrix}$$

which yields an error correlation of approximately 0.7 (correlation coefficient). The inverse of this matrix provides the weighting for these measurements when used in a least squares covariance analysis.

For stellar attitudes at times T_1 (0.0 sec) and T_4 , the design matrix for the covariance analysis is given by

$$A_{STELLAR} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ T_4^3 & T_4^2 & T_4 & 1 \end{bmatrix}$$

GLOBAL POSITIONING SYSTEM

The GPS measurements (phase) are assumed to be processed to obtain spacecraft orientation every second within the interval $[T_1 T_4]$:

$$\theta^o = \theta + v$$

where the errors v were assumed to be statistically independent. Accuracy levels of 36 arcsec (NRL program goal for 1995), 180 arcsec (demonstrated accuracy at the Naval Surface Warfare Center Dahlgren Division (NSWCDD)) and 500 arcsec were considered in the covariance analysis discussed below. Thus, the covariance matrix for the set of GPS derived orientations is given by

$$\Sigma_v = \begin{bmatrix} E[v_0 v_0] & 0 & 0 & \dots & 0 \\ 0 & E[v_2 v_2] & 0 & \dots & 0 \\ 0 & 0 & 0 & E[v_n v_n] & 0 \end{bmatrix}$$

The design matrix for the GPS derived orientations is given by

$$A_{GPS} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ t_2^3 & t_2^2 & t_2 & 1 \\ . & . & . & . \\ t_n^3 & t_n^2 & t_n & 1 \end{bmatrix}$$

where t_i is the number of seconds from T_1 (taken to be the time reference epoch in this analysis).

RATE GYRO

The rate gyro provides (by integration) the change in θ over any time interval $[t_1, t_2]$:

$$\Delta\theta_{12} = a(t_2^3 - t_1^3) + b(t_2^2 - t_1^2) + c(t_2 - t_1) + v_{12}$$

Although available at a higher rate, it was assumed that the gyro data would be sampled at a 1-sec rate from T_1 .

The error y in $\Delta\theta$ is the integrated effect of the gyro drift rate and thus, represents a correlated error signal throughout any 3-min interval. Two statistical gyro error models were considered. The first model represented constant drift noise with a 0.01333 arcsec/sec uncertainty, while the second model consisted of drift noise and drift noise rate:

$$\sigma_{\dot{\epsilon}\theta} = 0.01333 \quad (\text{Model 1})$$

$$\sigma_{\dot{\epsilon}\theta} = ut^{1/2} + vt^{3/2}$$

$$u = 0.01333 \quad (\text{Model 2})$$

$$v = 0.000079$$

where the units are arcsec/sec and t is in seconds from T_1 when the first stellar update is made. These error models were taken from LANDSAT 7 technical materials provided by DMA and represent the uncertainty in gyro drift at the one (1) sigma level.

Given that $\Delta\theta_{12}$ is the integrated output of the rate gyro over $[t_1, t_2]$, then the uncertainty in the error γ_{12} (assuming $t_1 = 0 = T_1$) is

$$\begin{aligned} \sigma_{\gamma_{12}} &= \int_0^{t_2} \sigma_{\dot{\epsilon}\theta} dt \\ \text{or} \quad &= 0.01333t_2 \quad (\text{Model 1}) \end{aligned}$$

$$= (2/3)ut_2^{3/2} + (2/5)vt_2^{5/2} \quad (\text{Model 2})$$

For two distinct times t_2 and t_3 , the errors in $\Delta\theta_{12}$ and $\Delta\theta_{13}$ will be correlated depending on the separation of t_2 from t_3 . The closer t_2 is to t_3 the higher will be the correlation since the errors as manifested by gyro drift become more identical.

For t_2 and t_3

$$\gamma_{13} = \gamma_{12} + \int_{t_2}^{t_3} \dot{\epsilon}\theta dt$$

Multiplying through by γ_{12} gives

$$\gamma_{13} \gamma_{12} = \gamma_{12} \gamma_{12} + \gamma_{12} \int_{t_2}^{t_3} \dot{\epsilon}\theta dt$$

Taking expectations yields

$$E[\gamma_{13} \gamma_{12}] = E[\gamma_{12} \gamma_{12}] + E\left[\gamma_{12} \int_{t_2}^{t_3} \dot{\epsilon}\theta dt\right]$$

The second term on the right-hand side of this last equation is the covariance between the accumulated error in the gyro alignment γ_{12} up to t_2 and the additional error, which accumulates between t_2 and t_3 . For the purposes of this analysis, it was assumed that these errors would be uncorrelated. Thus, the covariance between the errors γ_{12} and γ_{13} was taken as the variance of γ_{12} . This assumption essentially implies that the errors in gyro drift can be treated as a random walk. This assumption may be weak; however, no detailed performance data on the gyro types being considered for LANDSAT 7 were available to refine this assumption. Accordingly, the variance-covariance matrix for orientation changes after T_1 based on sampled rate gyro data is given by

$$\Sigma_Y = \begin{bmatrix} E[\gamma_{12}\gamma_{12}] & E[\gamma_{12}\gamma_{12}] & \dots & E[\gamma_{12}\gamma_{12}] \\ E[\gamma_{12}\gamma_{12}] & E[\gamma_{13}\gamma_{13}] & \dots & E[\gamma_{13}\gamma_{13}] \\ \cdot & \cdot & & \\ \cdot & \cdot & & \\ \cdot & \cdot & & \\ E[\gamma_{12}\gamma_{12}] & E[\gamma_{13}\gamma_{13}] & \dots & E[\gamma_{1m}\gamma_{1m}] \end{bmatrix}$$

The design matrix for gyro derived orientation changes $\Delta\theta$ from $t_1 = 0 = T_1$ to times t_i ($i = 2, \dots, m$) is given by

$$A_{GYRO} = \begin{bmatrix} t_2^3 & t_2^2 & t_2 & 0 \\ t_3^3 & t_3^2 & t_3 & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ t_m^3 & t_m^2 & t_m & 0 \end{bmatrix}$$

The times t_i occur each second after the first stellar update at time T_1 and end with the second stellar update at T_4 .

IMAGE MENSURATION

It was assumed that image mensuration at points separated by 250 km would provide relative orientation at image times T_2 and T_3 to a nominal accuracy of 5.8 arcsec. This uncertainty was based on a mensuration error of 1 pixel (5 m). The observation model for image pair mensuration is given by

$$\Delta\theta = \theta_3 - \theta_2 + \alpha$$

where θ_2 and θ_3 are the spacecraft orientations at image times T_2 and T_3 and α is the error in relative orientation derived from the mensuration process. The variance of the relative orientation $\Delta\theta$ is given by $E[\alpha\alpha]$.

The design matrix based on this observation is given by

$$A_{MENSURATION} = \begin{bmatrix} T_3^3 - T_2^3 & T_3^2 - T_2^2 & T_3 - T_2 & 0 \end{bmatrix}$$

COVARIANCE ANALYSIS

Using these data structures, data rates, and noise processes, least squares normal matrices were developed for each of the four observation types consistent with the image acquisition scenario of Figure 1:

$$A^T W A = A_1^T W_1 A_1 + A_2^T W_2 A_2 + A_3^T W_3 A_3 + A_4^T W_4 A_4$$

where for each observation type the weight matrix W_i is the inverse of the corresponding variance-covariance matrix for that observation type as given above. After formation, the matrix $A^T W A$ was inverted to produce the variance-covariance matrix for the determination of the attitude modeling parameters a , b , c , and d . Using this result, the uncertainty in spacecraft orientation at any time during the interval can be developed through linear error propagation using the following equation:

$$\Sigma_{\theta(t)} = \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix} \left[A^T W A \right]^{-1} \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix}^T$$

In particular, the uncertainty in $\theta(t)$ at image times T_2 and T_3 were of interest.

The results from this covariance analysis are given in Table 2 for various cases, which considered nominal measurement precision as well as certain variations in order to gain insight into the influence of each error source. Case 1 was based on the use of the nominal error statistics from Table 1. Cases 2 through 7 provided orientation results as a function of variations in the noise processes associated with the measurements.

Several conclusions can be drawn from the results of this preliminary analysis:

(1) Simple stereo pair mensuration has little impact on spacecraft attitude accuracy (Case 2 vs Case 4) since the correlated error in orientation of a stereo pair due to the stellar sensor cannot be reduced through mensuration.

(2) The variation in the gyro noise models considered here had no significant impact on the overall results (see Cases 1, 2, 6, and 7).

(3) Attitude accuracy during the imaging operation appears to be a linear function of stellar sensor accuracy (see Cases 2 and 5).

(4) GPS attitude determination worse than 180 arcsec has little impact on the results (Case 2 vs Case 3). If GPS attitude is improved significantly, to a level consistent with an NRL technology goal of 36 arcsec, then spacecraft attitude at the imaging times could be significantly improved (Case 1 vs Case 2 and Case 7 vs Case 6).

TABLE 2. COVARIANCE ANALYSIS RESULTS FOR LANDSAT 7 IMAGE PAIR
(180-SEC IMAGE OPERATION)

Case	GPS	Stellar	Gyro	Mensuration	Attitude Result
1	36	4.0/2.7	0.01333	5.8	2.3
2	180	4.0/2.7	0.01333	5.8	4.2
3	500	4.0/2.7	0.01333	5.8	4.4
4	180	4.0/2.7	0.01333	2.9	4.2
5	180	2.0/1.35	0.01333	5.8	2.2
6	180	4.0/2.7	$0.01333/t^{**0.5}$ $+0.000079/t^{**1.5}$	5.8	4.2
7	36	4.0/2.7	$0.01333/t^{**0.5}$ $+0.000079/t^{**1.5}$	5.8	2.3

Note: Attitude results are in units of arcseconds

SUMMARY

Although limited in scope, this analysis has provided an indication of the impact that certain measurement types would have on determining the attitude of the LANDSAT 7 spacecraft. It is clear that high precision attitude will depend critically on the accuracy of the stellar sensor system. Augmentation with GPS may prove useful if certain GPS technical goals can be achieved. However, the ability to exploit (in a metric sense) LANDSAT 7 imagery for mapping and charting using stand-alone stereo pairs may be marginal considering product standards for positional accuracy and the results from this analysis.

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